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(54) **METHODS AND SYSTEMS FOR PROVIDING CONSTANT-FEEL, MULTI-AXIS TACTILE CUES**

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G05D 3/00	(2006.01)
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(52) **U.S. Cl.**
CPC *B64C 13/503* (2013.01); *B64C 13/04* (2013.01); *B64C 13/46* (2013.01)

(58) **Field of Classification Search**
USPC 701/1–539; 244/223
See application file for complete search history.

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(57) **ABSTRACT**

A system for adjusting tactile cues includes a controller having an axis and a cross-axis; an axis tactile cue generated in response to the position of the controller along the axis; a position scaling unit scaling a cross-axis controller position to generate a scaled cross-axis controller position; a force scaling unit scaling a cross-axis controller force to generate a scaled cross-axis controller force; a combiner combining the scaled cross-axis controller position and the scaled cross-axis controller force to generate an adjustment factor; and an adjuster adjusting the axis tactile cue in response to the adjustment factor to generate an adjusted axis tactile cue.

16 Claims, 4 Drawing Sheets
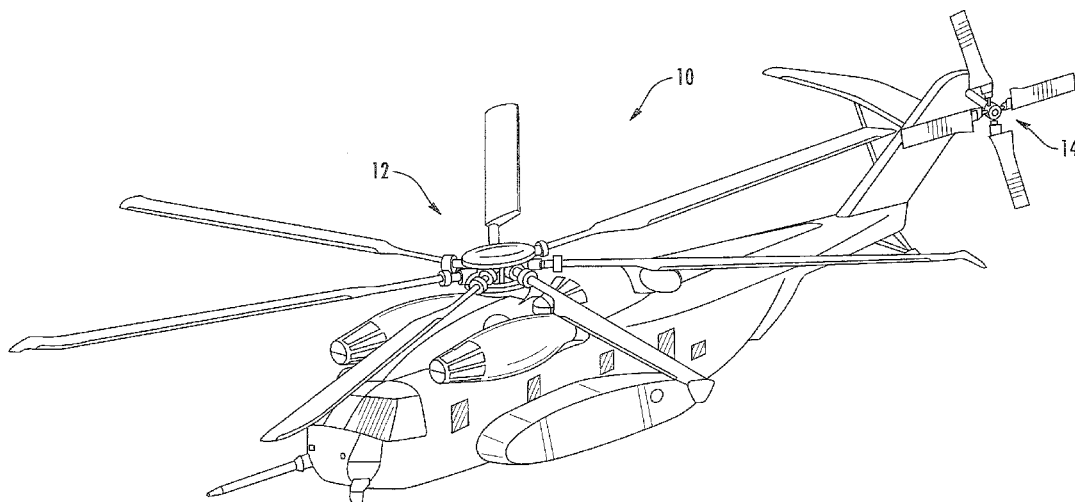
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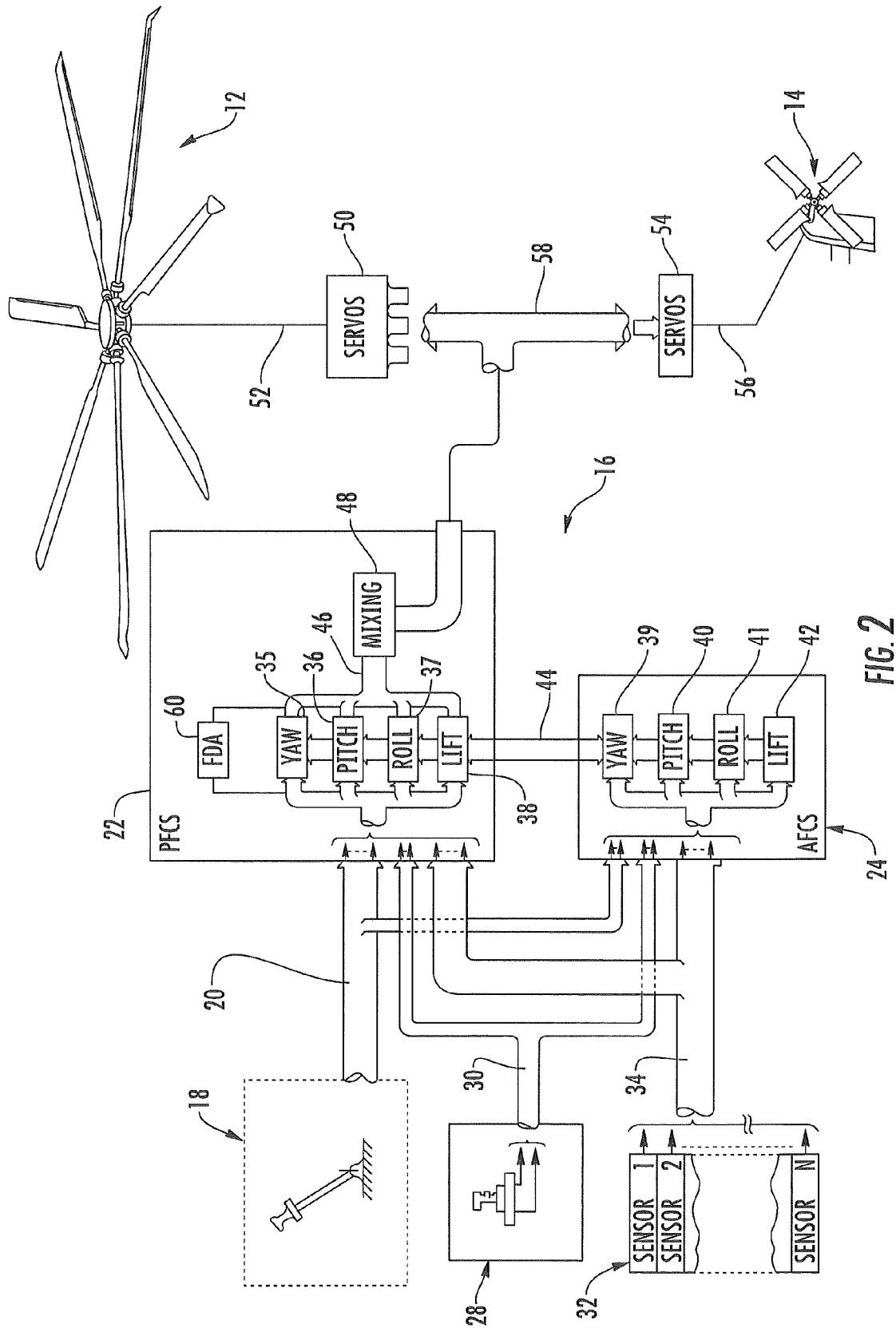### FOREIGN PATENT DOCUMENTS

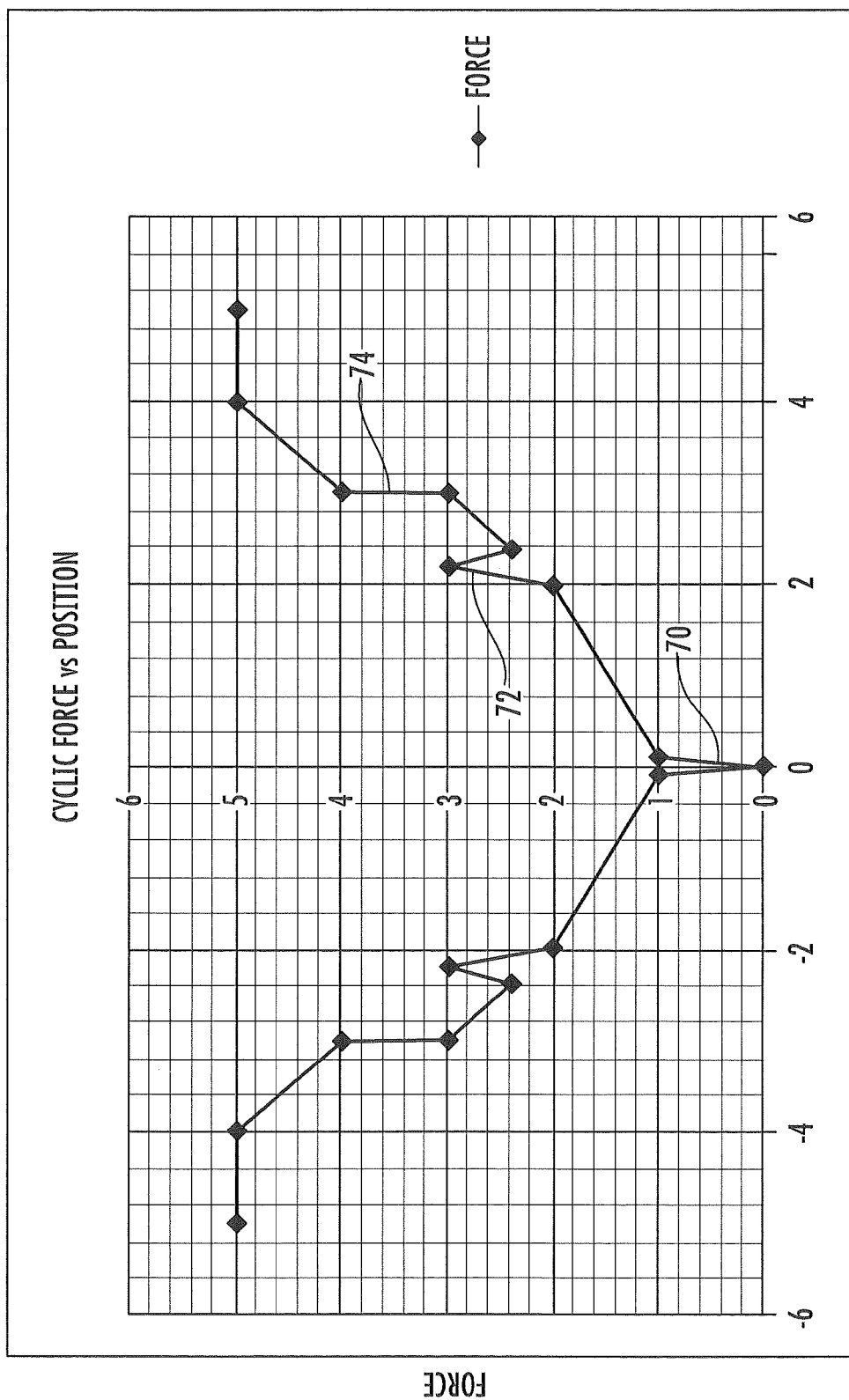|		
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FIG. 1

FIG. 2
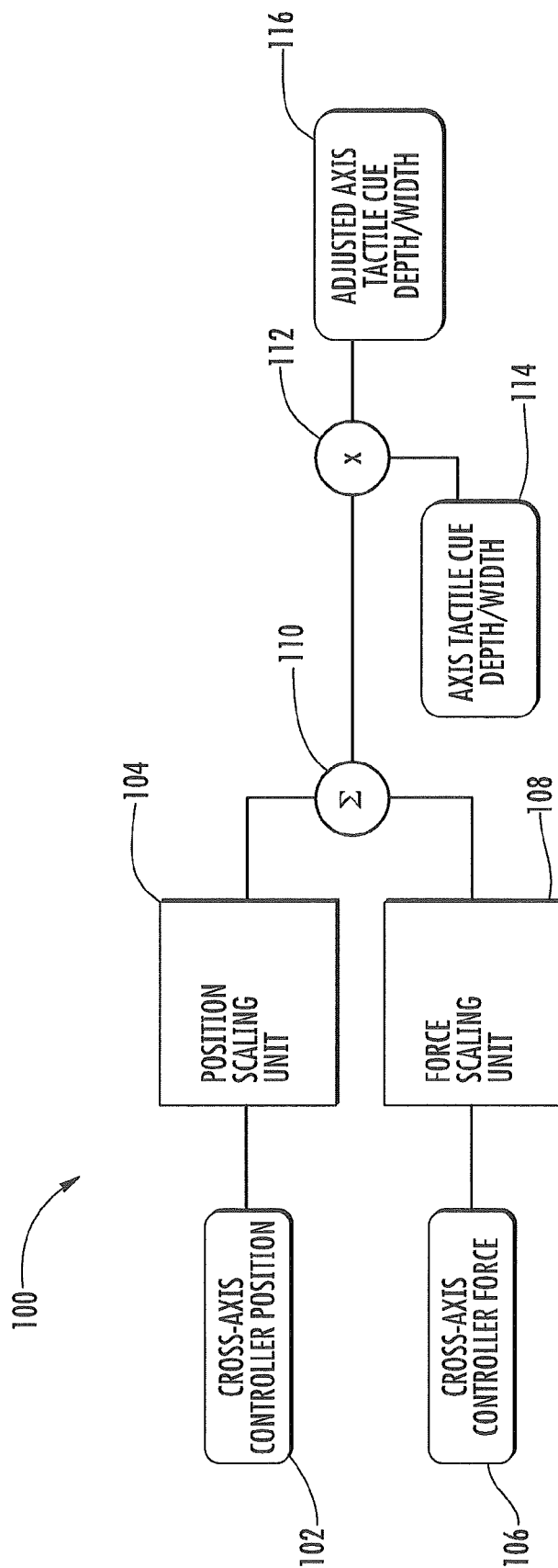
CYCLIC FORCE vs POSITION

FIG. 3
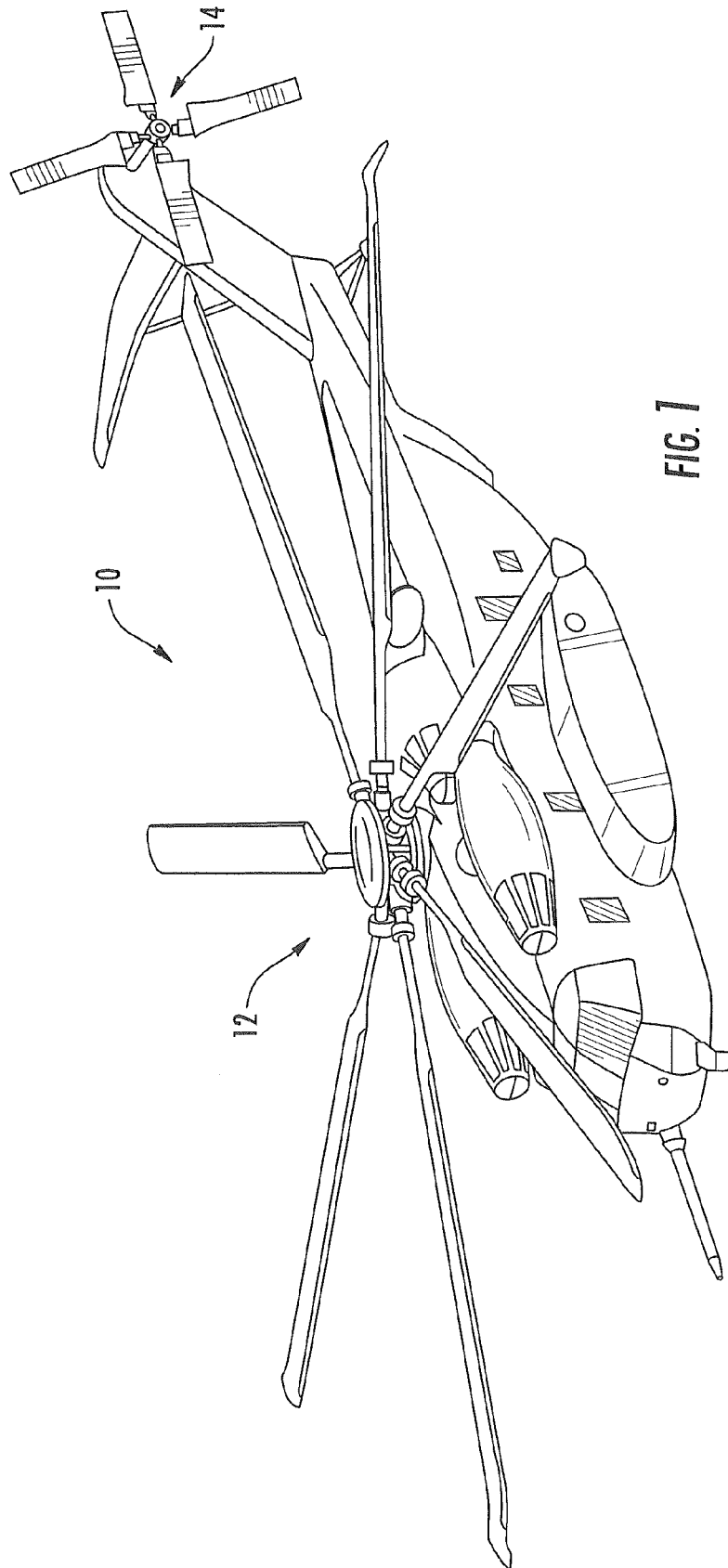
FIG. 4

METHODS AND SYSTEMS FOR PROVIDING CONSTANT-FEEL, MULTI-AXIS TACTILE CUES

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with Government support under W58RGZ-06-D-0045 awarded by the Department of the Army. The Government has certain rights in this invention.

BACKGROUND

The subject matter disclosed herein relates generally to providing tactile cues to an operator of a vehicle, and in particular to methods and systems for providing multi-axis tactile cues to an operator of a vehicle.

Many vehicles, including helicopters, use fly-by-wire (FBW) systems to control vehicle operation. Emerging FBW helicopters provide high levels of augmentation. These systems greatly reduce pilot workload and enhance safety. Early FBW helicopters utilized "passive" controllers. These passive controllers provide constant force feel to the pilots via simple spring/damper mechanisms. As the FBW technology matures, a preference for electronically variable force-feel has emerged. More recent FBW helicopters utilize "active" controllers, also known as active inceptors. These controllers contain high-bandwidth force motors/control systems that allow adjustment of many aspects of the controller feel. With these systems it is possible for the flight control system to provide a variety of tactile cues (such as power cues, level flight cues, control limit cues, etc.) to the pilot. Improvements in providing tactile cues to the pilot would be well received in the art.

SUMMARY

One embodiment includes a system for adjusting tactile cues including a controller having an axis and a cross-axis; an axis tactile cue generated in response to the position of the controller along the axis; a position scaling unit scaling a cross-axis controller position to generate a scaled cross-axis controller position; a force scaling unit scaling a cross-axis controller force to generate a scaled cross-axis controller force; a combiner combining the scaled cross-axis controller position and the scaled cross-axis controller force to generate an adjustment factor; and an adjuster adjusting the axis tactile cue in response to the adjustment factor to generate an adjusted axis tactile cue.

Another embodiment is a method for adjusting tactile cues for a controller having an axis and a cross-axis, the method including obtaining an axis tactile cue in response to a position of the controller along the axis; scaling a cross-axis controller position to generate a scaled cross-axis controller position; scaling a cross-axis controller force to generate a scaled cross-axis controller force; combining the scaled cross-axis controller position and the scaled cross-axis controller force to generate an adjustment factor; and adjusting the axis tactile cue in response to the adjustment factor to generate an adjusted axis tactile cue.

Other aspects, features, and techniques of the invention will become more apparent from the following description taken in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings wherein like elements are numbered alike in the several FIGURES, in which:

FIG. **1** is a perspective view of an exemplary rotary wing aircraft for use with embodiments of the invention;

FIG. **2** is a schematic diagram of an exemplary flight control system;

FIG. **3** depicts exemplary tactile cues for a control axis; and

FIG. **4** is a block diagram of a system for adjusting tactile cues in exemplary embodiments.

DETAILED DESCRIPTION

Embodiments FIG. **1** illustrates a general perspective view of an exemplary vehicle in the form of a vertical takeoff and landing (VTOL) rotary-wing aircraft **10** for use with embodiments of the invention. The rotary-wing aircraft **10** includes a main rotor assembly **12** and tail rotor assembly **14**. Although a particular helicopter configuration is illustrated and described in disclosed embodiments, other configurations and/or machines, such as high speed compound rotary-wing aircraft with supplemental translational thrust systems, dual contra-rotating, coaxial rotor system aircraft, turbo-props, tilt-rotors, tilt-wing aircraft, and fixed-wing aircraft will also benefit from embodiments of the present invention.

Referring to FIG. **2**, a fly-by-wire type flight control system **16** includes a model following control system which shapes the pilot's controller and displacement commands through an inverse vehicle model to produce the desired aircraft response. The system **16** includes a Primary Flight Control System (PFCS) **22** and an Automatic Flight Augmentation and Cuing System (AFCS) **24**.

The PFCS **22** is the flight critical portion of the flight control system, while the FACS **24** is the mission critical portion. The FACS **24** augments the performance of the PFCS **22**. The PFCS **22** and FACS **24** execute explicit model following control laws to provide both control and stability augmentation. In this control law architecture, pilot commands are shaped directly into desired aircraft responses. These desired commands are then passed through an inverse aircraft model to obtain the control commands required to produce the desired response. The difference between the desired command and the aircraft response is also fed back to drive these errors towards zero, thus improving the model following performance.

The PFCS **22** and FACS **24** each receive the force output command signals of a collective controller **18** on line **20**, a cyclic controller **28** on line **30**, and the aircraft's sensed parameter signals from sensors **32**, on lines **34**. The collective controller **18** and the cyclic controller **28** may take various forms including sidearm controllers, a yaw pedal system or other such flight controllers. The pilot command signals on lines **20**, **30** and the sensed parameter signals on lines **34** are shown consolidated within trunk lines **32** and **34** in the PFCS and FACS, respectively.

The PFCS **22** and FACS **24** may each contain separate control channel logic laws for controlling the yaw, pitch, roll and lift axes of the aircraft. The logic is included in the PFCS and FACS control modules (schematically represented by blocks **35-38** for the PFCS and blocks **39-42** for the FACS). The sensed parameter signals from aircraft sensors **32**, on lines **34**, provide the PFCS and FACS with the aircraft's angular rate and attitude response to the rotor command signals. The PFCS logic provides rotor command signals and the FACS logic provides conditioning and/or trimming of the PFCS four axis logic functions. The PFCS and FACS logic modules interconnect through bus **44** to provide rotor command signals on output lines **46** to a mixing function **48** which communicates commands on lines **58** for the displacement of servos **50** and linkages **52** to control the tip path plane of the

main rotor **12**. A mixed command signal is also provided on line **58** to the tail rotor servos **54** which control the thrust of the tail rotor **14** through linkages **56**.

Cyclic controller **28** is a multi-axis active controller (e.g., an active inceptor) that provides force feel to the control input (i.e., the stick) to provide cues to the operator. An issue presents itself as a designer tries to set the size of these cues. In the case of a center detent, for example, setting the depth too low will produce a detent that cannot be easily detected by the pilots and setting depth too high produces an undesirable breakout force. It is possible, with some experimentation to set the size of each cue to an optimal value. However, in the case of a cyclic controller or other multi-axis controller, the pilot is manipulating more than one axis at a time with the same hand. This results in an apparent change in sensitivity to the size of these cues. For example, a 0.75 lb (0.34 kg) center detent in the pitch axis might be quite perceptible if only pitch inputs are made (i.e. the controller is only moved in a single axis). If the pilot is commanding pitch and roll simultaneously, perceiving a 0.751 lb (0.34 kg) center detent in pitch becomes problematic due to 2-3 lbs (0.9-1.36 kg) of force in the roll axis. Embodiments adjust the tactile cues applied to the multi-axis controller based on the position of the controller in a cross-axis.

FIG. **3** depicts a sample plot of force versus position for a single axis (e.g., pitch) of a cyclic controller, designed to provide a variety of tactile cues to the pilot. In this scenario, several tactile cues are shown. A center detent **70** is present (the active inceptor is programmed to emulate a unique trim cyclic), a gate **72** is used to cue the pilot of power limits and a soft-stop **74** is used to cue control limits. The tactile cues may be described as having a depth (in force) and a width (in position). As noted above, if the pilot is only manipulating pitch, then these cues are easily noticeable by the pilot. If, however, the pilot is simultaneously adjusting pitch and roll, the pitch tactile cues may not be significant enough to be felt by the pilot, as the roll force is simultaneously applied to the controller.

FIG. **4** is a block diagram of a system **100** for adjusting tactile cues applied to a multi-axis controller in exemplary embodiments. System **100** may be implemented as part of the FACS **24** in FIG. **1**. System **100** adjusts the tactile cue (e.g., depth in force and/or width in position) based on the cross-axis controller position and cross-axis controller force applied to the controller. The cross-axis controller position **102** is input to a position scaling unit **104** to generate a scaled cross-axis controller position. Position scaling unit **104** may be a look-up table that indexes the scaled cross-axis controller position by the cross-axis controller position. Alternatively, the position scaling unit **104** may be implemented by a mathematical function. Similarly, the cross-axis controller force **106** is input to a force scaling unit **108** to generate a scaled cross-axis controller force. Force scaling unit **108** may be a look-up table that indexes the scaled cross-axis controller force by the cross-axis controller force. Alternatively, the force scaling unit **108** may be implemented by a mathematical function.

The scaled cross-axis controller position and scaled cross-axis controller force are then combined at combiner **110** to define an adjustment factor. Combiner **110** may be a simple summer, or may involve a more complex mathematical operation, a two-input look-up table, etc. The adjustment factor is then applied to an adjuster **112**, which adjusts the axis tactile cue **114** by the adjustment factor. The adjuster **112** may be a multiplier or may involve a more complex mathematical operation, a two-input look-up table, etc. The output of adjuster **112** is an adjusted axis tactile cue **116**.

To illustrate further, take an example where the axis tactile cue **114** corresponds to the soft gate **72** from FIG. **3** on the pitch axis of the cyclic controller **28**. In this example, the pilot is also adjusting roll by moving controller **28** along the cross-axis. The controller **28** will experience force feedback in response to the roll maneuver, making it more difficult for the pilot to feel the soft gate **72** tactile cue on the pitch axis. System **100** uses the cross-axis controller position and cross-axis controller force to adjust the soft gate cue **72** to increase the depth (i.e., force) and/or the width (i.e. position) of the soft gate cue **72** to render this tactile cue more perceptible by the pilot.

Embodiments provide compensation to account for cross-axis feel and greatly open the design space for tactile cueing in multi-axis controllers. Embodiments allow the pilot to make large inputs in one axis, while retaining the other axis in a center detent, which is a desirable characteristic for a FBW controller and facilitates meeting handling qualities specifications. Although embodiments have been discussed with reference to a multi-axis controller for a helicopter, it is understood that features may be applied to other systems using multi-axis, active controllers providing tactile cues to operators. Further, only a single cross-axis is depicted in FIG. **4**. It is understood that embodiments may use position and force from more than one cross-axis to alter tactile cues on an axis. Further, the axes involved need not be perpendicular to utilize embodiments of the invention.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. While the description of the present invention has been presented for purposes of illustration and description, it is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications, variations, alterations, substitutions, or equivalent arrangement not hereto described will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. Additionally, while various embodiment of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. A method for adjusting tactile cues for a controller having an axis and a cross-axis, the method comprising;

obtaining an axis tactile cue in response to a position of the controller along the axis;

scaling a cross-axis controller position to generate a scaled cross-axis controller position;

scaling a cross-axis controller force to generate a scaled cross-axis controller force;

combining the scaled cross-axis controller position and the scaled cross-axis controller force to generate an adjustment factor; and

adjusting the axis tactile cue in response to the adjustment factor to generate an adjusted axis tactile cue to be applied along the axis of the controller;

wherein the axis tactile cue has a depth and a width, and the adjusted axis tactile cue has one of an adjusted depth and an adjusted width;

wherein the axis and cross-axis are perpendicular;

wherein the controller is coupled to a servo, the servo coupled to a linkage to control a rotor of a rotary wing aircraft;

wherein the controller is coupled to the servo in a fly-by-wire system with no direct mechanical connection

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between the controller and the servo and with no direct mechanical connection between the controller and the linkage.

2. The method of claim **1** wherein scaling the cross-axis controller position is performed by a look up table indexing the scaled cross-axis controller position by the cross-axis controller position.

3. The method of claim **1** wherein scaling the cross-axis controller position is performed by a mathematical operation on the cross-axis controller position to generate the scaled cross-axis controller position.

4. The method of claim **1** wherein scaling the cross-axis controller force is performed by a look up table indexing the scaled cross-axis controller force by the cross-axis controller force.

5. The method of claim **1** wherein scaling the cross-axis controller force is performed by a mathematical operation on the cross-axis controller force to generate the scaled cross-axis controller force.

6. The method of claim **1** wherein the combining includes summing the scaled cross-axis controller position with the scaled cross-axis controller force to generate the adjustment factor.

7. The method of claim **1** wherein the adjusting includes multiplying the axis tactile cue by the adjustment factor to generate the adjusted axis tactile cue.

8. A system for adjusting tactile cues comprising:

a controller having an axis and a cross-axis;

an axis tactile cue generated in response to the position of the controller along the axis;

a position scaling unit scaling a cross-axis controller position to generate a scaled cross-axis controller position;

a force scaling unit scaling a cross-axis controller force to generate a scaled cross-axis controller force;

a combiner combining the scaled cross-axis controller position and the scaled cross-axis controller force to generate an adjustment factor; and

an adjuster adjusting the axis tactile cue in response to the adjustment factor to generate an adjusted axis tactile cue to be applied along the axis of the controller;

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wherein the axis tactile cue has a depth and a width, and the adjusted axis tactile cue has one of an adjusted depth and an adjusted width;

wherein the axis and cross-axis are perpendicular;

wherein the controller is coupled to a servo, the servo coupled to a linkage to control a rotor of a rotary wing aircraft;

wherein the controller is coupled to the servo in a fly-by-wire system with no direct mechanical connection between the controller and the servo and with no direct mechanical connection between the controller and the linkage.

9. The system of claim **8** wherein the position scaling unit is a look up table indexing the scaled cross-axis controller position by the cross-axis controller position.

10. The system of claim **8** wherein the position scaling unit performs a mathematical operation on the cross-axis controller position to generate the scaled cross-axis controller position.

11. The system of claim **8** wherein the force scaling unit is a look up table indexing the scaled cross-axis controller force by the cross-axis controller force.

12. The system of claim **8** wherein the force scaling unit performs a mathematical operation on the cross-axis controller force to generate the scaled cross-axis controller force.

13. The system of claim **8** wherein the combiner is a summer summing the scaled cross-axis controller position with the scaled cross-axis controller force to generate the adjustment factor.

14. The system of claim **8** wherein the adjuster is a multiplier multiplying the axis tactile cue by the adjustment factor to generate the adjusted axis tactile cue.

15. The system of claim **8** wherein the axis tactile cue has a depth and a width, and the adjusted axis tactile cue has both an adjusted depth and an adjusted width.

16. The system of claim **8** wherein the axis corresponds to pitch and the cross-axis corresponds to roll.

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